Investigation of Pulse Pedestal and Dynamic Chirp Formation on Picosecond Pulses After Propagation Through an SOA

A. M. Clarke, M. J. Connelly, P. Anandarajah, L. P. Barry, and D. Reid

***Abstract*—The authors investigate the propagation of picosecond pulses through semiconductor optical amplifiers using the measurement technique of frequency resolved optical gating. The work shows the generation of significant pulse pedestals and frequency chirp across the optical pulses, which initially have a duration of 2 ps. As the input peak power of the optical pulses is increased from 2.4 to 80 mW, the pulse pedestals increased by 20 dB and the chirp became significantly more nonlinear. The generated pedestals and the nonlinear output chirp may cause serious degradation in high-speed communications systems employing wavelength-division-multiplexing and optical time-division-multiplexing techniques.**

***Index Terms*—Frequency chirp, optical communications, optical pulse measurements, semiconductor optical amplifier (SOA).**

I. Introduction

SEMICONDUCTOR optical amplifiers (SOAs) are attracting a lot of interest in the field of telecommunications due to their high gain, small size, and opportunities for integration and low cost [1]. As telecommunication systems move toward higher capacities, it is essential to examine the operation of SOAs in high bit rate communication systems. Specifically, it is vital to investigate the effect of SOAs on picosecond optical pulses that may be employed in photonic systems operating at line rates of 40, 80, and 160 Gb/s. Presently, picosecond pulse sources [2] can generate high-quality pulses that have minimal chirp and jitter, and high (>30 dB) temporal and spectral purity as determined by the temporal extinction ratio, and the sidemode suppression ratio, respectively. These are required parameters for the practical use of these pulse sources in high-speed optical time-division-multiplexed (OTDM) transmission systems [2]. If future OTDM communication systems are going to employ SOAs, it is, thus, necessary to investigate the effects on picosecond pulses as they propagate through SOAs. This work focuses on the effects of SOA propagation and amplification on 2-ps pulses generated by a mode-locked laser source that may be suitable for OTDM systems operating at data rates from 40 to 160 Gb/s. We also explore the temporal shape of the induced chirp by the SOA, which will also be of vast importance for SOA-based interferometers used as all-optical switches.

Pulse propagation through SOAs has been experimentally investigated previously by traditional methods of autocorrelation, cross correlation, and optical spectrum analysis [3], [4]. However, the relatively new measurement scheme of frequency resolved optical gating (FROG) [5] may be used to overcome the limitations of traditional methods and provides complete characterization in the spectral and temporal domains with corresponding phase information. Previous work using FROG to characterize pulse propagation in SOAs has examined pulse distortion for pulsewidths around 200–300 fs in the absorption, transparency and gain regimes [6], and has examined nonlinear gain dynamics in the picosecond regime [7]. However, the pulse sources used in these works are not suitable for practical high-speed communications systems based on OTDM. In this letter, we present a complete analysis of the effect of SOA amplification on 2-ps mode-locked pulses generated at repetition rates of 10 GHz, which would be suitable for multiplexing to 40–160-Gb/s data rates. Our results are concerned primarily with the frequency chirp induced on the pulses by the SOA (an area that has seen extensive theoretical studies [8], [9]), and the introduction of temporal pedestals after pulse amplification in the SOA. We have characterized both of these effects (frequency chirp and temporal pedestals) for input pulse peak powers to the SOA ranging from 2.4 to 80 mW. Our results show the exact profile of the frequency chirp induced by the SOA for the range of optical input powers, and also an increase in the temporal pulse pedestal, induced by the SOA, of 20 dB as the input pulse peak power is increased. We also present results showing how a filter can be used to enhance the performance of SOAs for use in an OTDM system.

II. Experiment

The experimental setup is shown in Fig. 1. The pulses were generated using a commercially available mode-locked laser generating 5-ps pulses at a repetition rate of 10 GHz, and operating at a wavelength of 1534 nm. The pulses from the mode-locked laser have a significant linear frequency chirp, which is used to compress the pulses down to duration of 1.8 ps using dispersion-compensating fiber. The resultant Gaussian optical pulses are nearly transform limited, exhibiting a time bandwidth product of 0.5. A variable optical attenuator is then used to vary the input power of the optical pulses injected

Manuscript received February 24, 2005; revised May 9, 2005. This work was supported by Science Foundation Ireland Investigator Grant 02/IN1/I42.

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Digital Object Identifier 10.1109/LPT.2005.852324

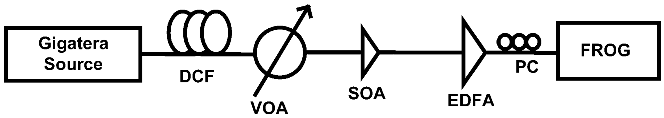

Fig. 1. Experimental setup.

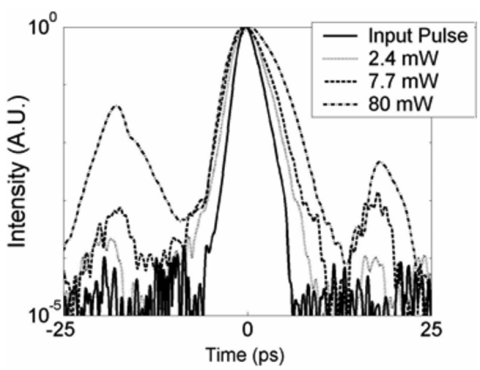

Fig. 2. Temporal profile of the input pulse and the pulse after the SOA with an input peak power of 2.4, 7.7, and 80 mW.

into the SOA. The SOA (from Kamelian) has an unsaturated fiber-to-fiber gain of 25 dB at an operating current of 250 mA.

Analysis of the pulses is carried out before and after amplification using a second-harmonic generation FROG with a spectral resolution of 0.05 nm (6 GHz). The FROG generates a spectrogram, which is a three-dimensional plot of intensity as a function of wavelength and time. A phase retrieval program is then applied to the generated spectrogram to reconstruct the electric field of the optical pulse giving complete spectral and temporal characterization of the measured pulse. To obtain good signal-to-noise ratio (SNR) in the FROG measurements, and to minimize the time taken to acquire the results, an erbium-doped fiber amplifier (EDFA) is employed to amplify the input pulses to the FROG to a peak power of around 500 mW. The EDFA used is designed specially for operation with 2-ps optical pulses, and it is operated in the linear gain regime such that it does not alter the phase of the optical pulses being characterized by the FROG. Frog errors below $\sim$0.004 were recorded for the retrieved pulses indicating accurate retrievals [5].

III. Results and Discussion

In this work, we initially analyze the physical effects on the pulse as it propagates through the SOA. The pulse pedestals and the frequency chirp induced on the optical pulses after amplification with the Kamelian SOA were examined as a function of input peak power to the amplifier. Fig. 2 displays the intensity profile of the input optical pulse and the temporal profile of the pulse after amplification by the SOA as the input peak power is varied from 2.4 to 80 mW, at a bias current of 200 mA. Fig. 2 shows that the pulsewidth increases from 1.8 to 4.2 ps. We can also see a dramatic increase in the pedestals on the leading and trailing edge of the pulse. For the pulses at the input to the SOA, the pedestals cannot be seen as they are below the noise level of our measurement system. At the output of the SOA, the pulse pedestals increase from approximately 40–15 dB below the peak of the pulse, as the input pulse peak power is increased. The

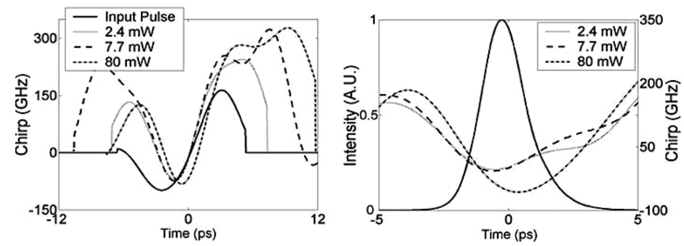

Fig. 3. (a) Chirp before and after the SOA and (b) the chirp induced by the SOA across the temporal profile of the pulse for input peak powers of 2.4, 7.7, and 80 mW.

reason for the decrease in the pulse pedestal suppression ratio is that the pulse pedestal present on the leading edge of the input pulse is amplified by the SOA as it sees a high linear gain. This partially saturates the amplifier gain leading to a reduced amplification of the main pulse. The high power main pulse then drives the SOA further into saturation. This is the reason for the asymmetric shape of the pulse outputted from the SOA, as the leading edge saturates the amplifier and the gain available for the trailing edge is reduced [8], [9]. The gain partially recovers for the trailing pedestal and it is, thus, also amplified relative to the main pulse. The central component of the 80-mW input pulse experiences higher gain saturation than is the case for the lower input power pulses. This implies that the relative intensity differences between the leading and trailing pedestals, and the main pulse, is less than is the case for lower power input pulses, which is shown from our results. For all of the input pulse powers, there is partial recovery of the gain after the main pulse but not as much as for the leading edge. This explains the observation that the relative effect of changing from 7.7 to 80 mW is larger than the effect of changing from 2.4 to 7.7 mW in the case of the leading pedestal. It should be noted that for the FROG measurements of the weak pedestals (>35 dB below pulse peak), the SNR of these pulses is such that there will be uncertainty as to the exact level of the weak pedestals. There is, however, no uncertainty in the large increase in these pedestals, which would clearly pose significant problems (through intersymbol interference) for the use of these pulses in high-speed OTDM systems [10].

Pulse chirp is an essential parameter used in the analysis of pulses in transmission systems as it determines the propagation distance of the pulse and it can give information about the pulse structure. It is important not only to know its peak-to-peak value but also its profile across the pulse, especially SOA-induced chirp as it has a nonlinear structure. Fig. 3(a) displays the profile of the frequency chirp across the pulses at the input and output of the SOA (for a range of input powers), and it is clear that the chirp becomes more nonlinear as the input power to the SOA is increased. The chirp ends abruptly close to the edges of the main pulse, as when the intensity level is close to zero, it is not possible to correctly measure the chirp (thus, it is set to zero at these levels). Fig. 3(b) displays the actual chirp induced by the SOA across the pulse. This chirp can be calculated by subtracting the input chirp of the compressed mode-locked laser pulses, from chirp at the output of the SOA [8]. The associated spectra of the optical pulses are illustrated in Fig. 4. Fig. 4(b) displays the spectrum of the amplified pulses from the FROG measurement,

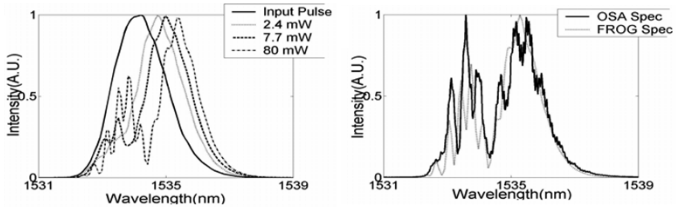

Fig. 4. (a) Spectra generated by the FROG for the input and output at input peak powers of 2.4, 7.7, and 80 mW and (b) a comparison of the spectrum generated by the FROG and the OSA at 80-mW input pulse peak power.

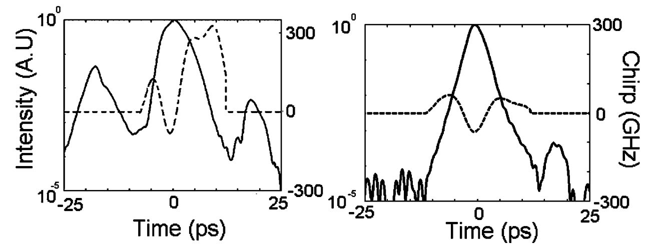

Fig. 5. Comparison of the temporal profile and the chirp output from the SOA (a) before and (b) after the simulated filter.

and that measured using an optical spectrum analyzer (OSA) when the input peak power to the SOA is 80 mW. These traces show reasonably good agreement, indicating the accuracy of the FROG technique.

The chirp across the leading edge of the pulse has a negative slope, which corresponds to the main peak of the spectrum shifting to longer wavelengths (often referred to as red-shifting). The chirp across the trailing edge has a positive slope. The second less dominant peak in the spectrum corresponds to the wings of the pulse and the pulse pedestals. The increase in the blue-shifted peak of the spectrum increases in line with the increases in pulse pedestals. These effects in the chirp are caused by self-phase modulation (SPM) induced by gain saturation caused by carrier depletion and carrier heating due to effects of stimulated emission, free carrier absorption, and in particular two-photon absorption [9], [11]. An additional contribution to SPM originates from the instantaneous nonlinear index [9]. The nonlinear effects are particularly important for pulsewidths below 2 ps [9]. Together all these effects result in gain suppression and a corresponding change in phase through the process of SPM.

It has been shown that by filtering out the unwanted blue-shifted component of the spectrum, the pulse from the SOA can be recovered to nearly its original form and the extinction ratio can be improved [12]. To demonstrate this, we used a theoretical simulation to apply an ideal bandpass filter with a bandwidth of 4 nm to the electric field produced by the FROG to remove the short wavelength components. The results illustrated in Fig. 5 show the reduction of the pulse pedestals to 30 dB below the peak and the pulsewidth reduced to a full-width at half-maximum of 2 ps. The nonlinear chirp is reduced, however there is some residual nonlinear chirp on the filtered pulse.

IV. Conclusion

This letter has investigated the effect of SOA amplification on 2-ps optical pulses using the FROG measurement technique. We have investigated in detail the reduction in pulse pedestal suppression ratio as the input power to the SOA is increased. We have also accurately measured the chirp after the SOA and the chirp induced by the SOA. Our results show that if SOAs are to be employed in high-speed optical communication systems, then it will be vital to optimize their operating characteristics in order to minimize the degradation in system performance that they may cause.

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